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Two students were supported under the Department of Defense Augmentation Awards for Science and Engineering Research Training (AASERT) Program. Mr. Mark McMurray was supported from 15 August 1992 through 14 August 1994, and Mr. Christopher Jones was supported from 15 August 1994 through 14 August 1995. Mark McMurray completed his M.S. degree and accepted employment at Champion Spark Plug Company. Chris Jones expects to complete the requirements for his M. S. degree by August 1996. Mr. McMurray's research pertained to the study of the effects of incomplete fuel-air mixing on the emission of oxides of nitrogen (Nox) and stability characteristics of lean premixed gas turbine combustors. Mr. Jones' research addressed the use of active control to inhibit combustion instabilities in gas turbine combustors.

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"Flame Turbulence Interactions - AASERT"

Grant Period: 15 June 92 to 14 August 95

Grant Monitor: Dr. Julian M. Tishkoff

Principal Investigator: Domenic A. Santavicca
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April 10, 1996

Final Report

Two students were supported by the AASERT Program on Air Force Grant No. F49620-92-J-0350. Mr. Mark McMurray was supported from August 15, 1992 through August 14, 1994 and Mr. Christopher Jones was supported from August 15, 1994 through August 14, 1995. Mark McMurray completed his M.S. degree and is currently working for Champion Spark Plug. Chris Jones is continuing to work on his M.S. degree which he is expected to complete by August 1996.

Mr. McMurray's research pertained to the study of the effects of incomplete fuel-air mixing on the NO_x emissions and stability characteristics of lean premixed gas turbine combustors and is summarized in Appendix A. Mr. Jone's research pertains to the use of active control to inhibit combustion instabilities in gas turbine combustors and is summarized in Appendix B.

APPENDIX A

Anticipated environmental regulations will preclude the use of conventional gas turbine engine combustion technology. Near stoichiometric combustion conditions in staged rich/quench/lean, and direct injection combustors will not be able to reach future sub 10 ppm NO_x requirements. Lean premixed combustors are capable of very low NO_x emissions, provided that the combustion gases are truly premixed so as to avoid any locally fuel rich zones. The formation of NO_x is extremely temperature sensitive and thus any locally fuel rich zones (ϕ>0.6) in the combustion gases would be detrimental to combustor emissions performance. Additional problems with lean premixed combustors include flame stability and narrow operating limits. Flame stability and relight capability are especially important in aeropropulsion applications.

The objectives of the current research were first to quantify the unmixedness in a typical coaxial jet combustor, then to use this measure of unmixedness to determine the effect of fuel and air mixing on flame stability and NO_x emissions. First, the combustor operating limits were determined over a range of inlet air Reynolds numbers for both a "premixed" and an "unmixed" case. Next, a typical operating point was established and emissions measurements were taken along the axis of the combustor and over a range of equivalence ratios. Finally, the air and fuel mixture was replaced with nitrogen and a 6500 ppm nitrogen dioxide seed gas, in a balance gas of nitrogen, for the mixing study which used the NO_2 fluorescence technique. Inlet Reynolds numbers were matched to those from the emissions study and relationships between fuel and air mixing, lean operating limits, and NO_x emissions were determined.

Flame stability was found to improve and the lean operating limits were extended with increased unmixedness. Initial fuel and air unmixedness was determined to play a major role in total NO_x formation, i.e. NO_x emissions increased substantially with increasing unmixedness. Also, the mixing within the combustor was found to improved significantly in the vicinity of the flame holder. thus, the flame holder played a major role in the mixing process. Additionally, the quartz tube combustor must be in place to avoid entrainment of the surrounding air. Previous studies have often removed both the flame holder and the combustor tube prior to taking the mixing measurements. Mixing data obtained without the combustor tube can not be related to emissions data. Additional experiments also showed that the mixedness in this system was independent of the Reynolds number over the range of Reynolds numbers tested, 1400-4000.

APPENDIX B

Current environmental regulations for both land-based and aircraft gas turbines focus mainly on NO_x emissions. One approach to reduce these emissions is to burn fuel lean, premixed, and prevaporized. The problem encountered is that regions of potentially damaging unsteady combustion exist under these conditions and therefore limit the range of NO_x reduction tests. By increasing the stability limits through active control, new stable regions will be created for investigating NO_x emissions.

When combustion takes place in an acoustic resonator, the interaction between acoustic pressure waves and unsteady heat release can lead to oscillations of potentially damaging intensity. Significant research has been conducted in the area of active control of these oscillations and one of the most practical and promising techniques is the introduction of a periodic secondary fuel injection near the base of the flame. The research reported in this paper centers on the control of combustion oscillations in a coaxial dump combustor using a closed loop control system that actuates a high speed solenoid valve secondary fuel injector. Depending on the flow conditions, various degrees of control can be achieved (and quantified in terms of the attained noise reduction) by optimization of the control parameters, including % secondary fuel, phase shift, trigger threshold, control frequency, and injection velocity.

Experiments were conducted on a coaxial dump combustor operated at atmospheric pressure. The fuel used was methane, where the fuel-air mixing was varied by changing the split between upstream and downstream fuel inlets. This allowed for a full range (100% to 0%) of premixing in an effort to reproduce realistic operating conditions. A simple X-shaped flame holder, fabricated from 1 mm diameter stainless steel rod, was positioned at the entrance to the combustor section. The combustor section is a 45 mm diameter quartz tube, total length of 18", and effective acoustic length of 16". The secondary fuel injection occurs at the base of the flame where the mixing tube and quartz combustor section meet and is delivered through a specially designed modular injector (figure 1). The injector has 8 angled, radially spaced 1/32" diameter holes through which the secondary fuel enters the combustion zone. High frequency, short duration fuel pulses are achieved with a high speed solenoid valve driven by General Valve's Iota One system. It is capable of operating at 250 Hz with pulse durations in the microseconds. The output of a sound level meter, positioned a the combustor exit, is used as the feedback for the control system. The meter's signal is processed so that the phase, secondary fuel injection frequency, and trigger threshold can be adjusted before the signal is sent to the valve driver.

Rayleigh's criterion states that when pressure perturbations associated with acoustic resonance and unsteady heat release rates are in phase, longitudinal pressure waves propagating in the duct can become destructively large in magnitude.[1] Thus, it is important to identify the source of the acoustic resonance. The frequency of the combustion instability was found to be dependent upon this length of tubing and the intensity of the instability was mainly a function of the bulk velocity and equivalence ratio. These results agree with the previous findings of Sivasegaram for dump combustors.[2] Since the effective length of the quartz tube used in these experiments was 16", the frequency was approximately 340 Hz, depending on the air temperature in the combustor.

The characteristics of the secondary fuel injection system were investigated using shadowgraph visualization techniques and a high speed camera which recorded 4000 frames per second. Over a range of frequencies from 100 Hz to 20 Hz and with various on/off times,

the valve and injector proved to be proficient at firing distinct, repeatable fuel pulses. Additionally, using a strobe light with this system, the delay time from when the valve is signaled to open until the fuel actually enters the combustor is about 3 ms, approximately one period of the pressure oscillations in the combustor.

Control of the combustion oscillations and a 10 to 12 dB noise level reduction was achieved by injecting less than 15% (of the total fuel) secondary fuel at a maximum frequency of 85 Hz, one-quarter of the oscillation frequency, and for a 2.75 ms pulse duration. Figure 2 shows the influence of phase angle and injection threshold parameters on the noise level reduction. It is clear that over a 70 degree phase angle range, corresponding to fuel injection just before the peak of the pressure wave, a distinct noise attenuation is achieved. For both the curves, the mean sound level without control was 108 dB; the difference between the two is the injection threshold setting. The upper curve has a higher threshold value and it therefore requires a larger pressure oscillation to trigger the valve. Under this condition, the valve fires less often, using a lower percentage of secondary fuel, but is not as effective at mitigating the sound. The lower curve represents the optimal threshold setting where a maximum noise reduction occurs with the minimal amount of secondary fuel (i.e., at a certain point lowering the threshold setting has little effect on the degree of control). The importance of threshold is also shown in figures 3 and 4. These figures depict the pressure wave and fuel injections for a high and low threshold setting, respectively. It appears that the oscillations grow exponentially until a fuel injection occurs and shortly after are reduced to an insignificant level. Figure 4 shows that a lower threshold setting clips the oscillation growth at a decreased stage and effectively reduces the mean sound level.

REFERENCES:

(1) Langhorne, P.J., Dowling, A.P., Hooper, N. "Practical Active Control Systems for Combustion Oscillations" *J. Propulsion* Volume 6, number 3. Page 324. 1989.
(2) Sivasegaram, S., and Whitelaw, J.H. "Oscillations in Axisymmetric Dump Combustors" *Combustion Science and Technology*. Volume 42. Pages 413-420. 1987.

FIGURE 1

Control System

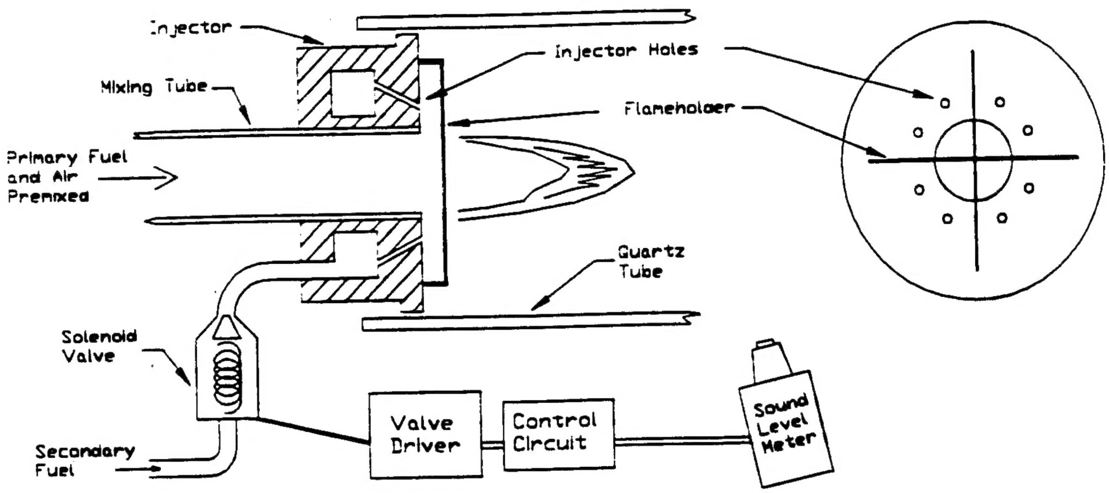

FIGURE 2

Mean sound level vs. phase

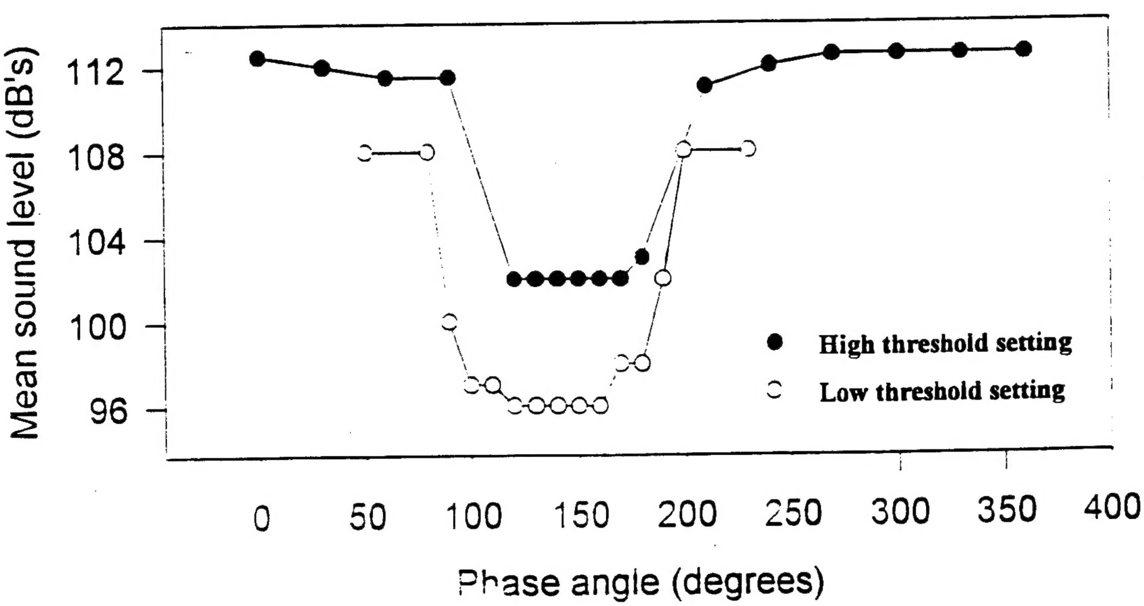

FIGURE 3

Pressure and Valve Signals

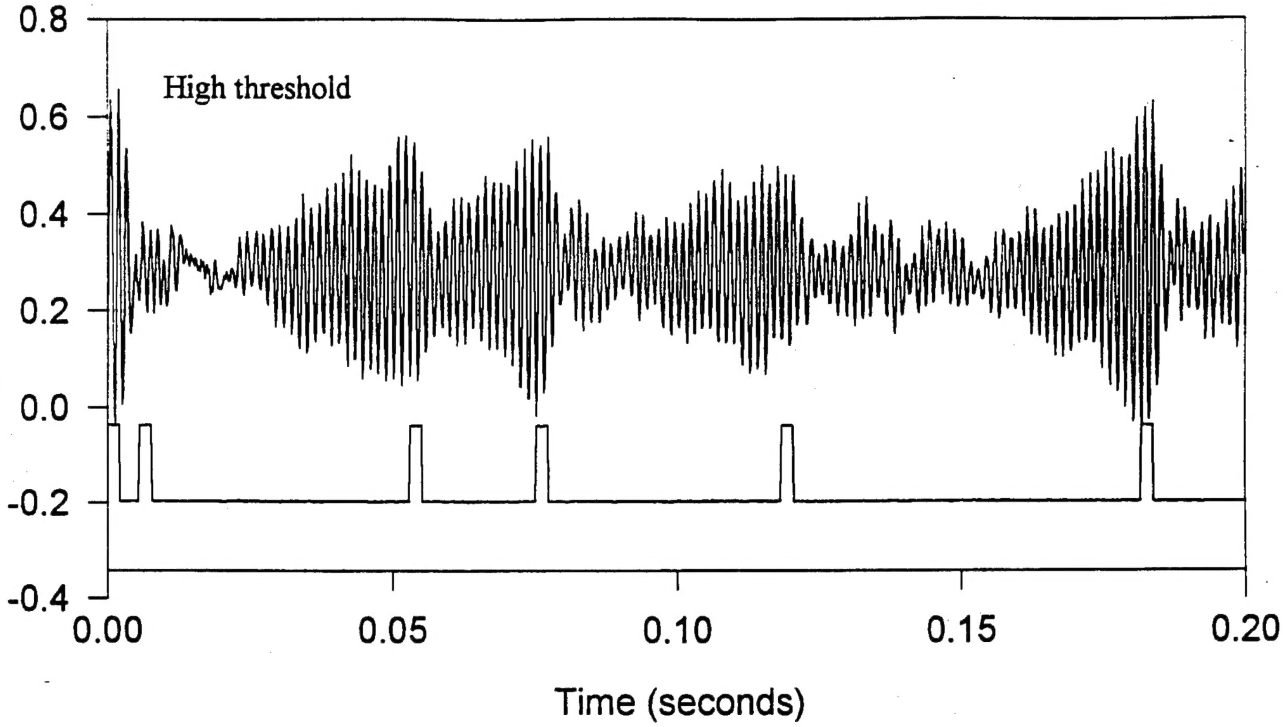

FIGURE 4